

Soil and soil organic carbon redistribution on the landscape

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Abstract

Patterns of soil organic carbon (SOC) vary widely across the landscape leading to large uncertainties in the SOC budget especially for agricultural landscapes where water, tillage and wind erosion redistributes soil and SOC across the landscape. It is often assumed that soil erosion results in a loss of SOC from the agricultural ecosystem but recent studies indicate that soil erosion and its subsequent redistribution within fields can stimulate carbon sequestration in agricultural ecosystems. This study investigates the relationship between SOC and soil redistribution patterns on agricultural landscapes. Soil redistribution (erosion and deposition) patterns were estimated in three tilled agricultural fields using the fallout ¹³⁷Cesium technique. ¹³⁷Cs and SOC concentrations of upland soils are significantly correlated in our study areas. Upland areas (eroding) have significantly less SOC than soils in deposition areas. SOC decreased as gradient slope increases and soils on concave slopes had higher SOC than soils on convex slopes. These data suggest that soil redistribution patterns and topographic patterns may be used to help understand SOC dynamics on the landscape. Different productivity and oxidation rates of SOC of eroded versus deposited soils also contribute to SOC spatial patterns. However, the strong significant relationships between soil redistribution and SOC concentrations in the upland soil suggest that they are moving along similar physical pathways in these systems. Our study also indicates that geomorphic position is important for understanding soil movement and redistribution patterns within a field or watershed. Such information can help develop or implement management systems to increase SOC in agricultural ecosystems.

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Keywords: Soil organic carbon; SOC; Carbon; Landscape; Soil erosion; Soil deposition; Topography; Slope

1. Introduction

The increase in CO₂ in the atmosphere over the past century has raised interest in the potential of agricultural ecosystems to sequester carbon (Gregorich et al., 1998; Stallard, 1998; Harden et al., 1999;

Schlesinger, 2000; Follett, 2001; Sperow et al., 2003; Lal, 2004; Freibauer et al., 2004; Janzen, 2004). Spatial and temporal patterns of soil organic carbon (SOC) have been shown to be a function of soil redistribution, vegetative productivity, mineralization of SOC, landscape position and management (Gregorich et al., 1998; Sauerbeck, 2001; West and Marland, 2003; Jacinthe et al., 2004). Water, tillage and wind erosion contribute significantly to the redistribution of soil and SOC across the landscape,

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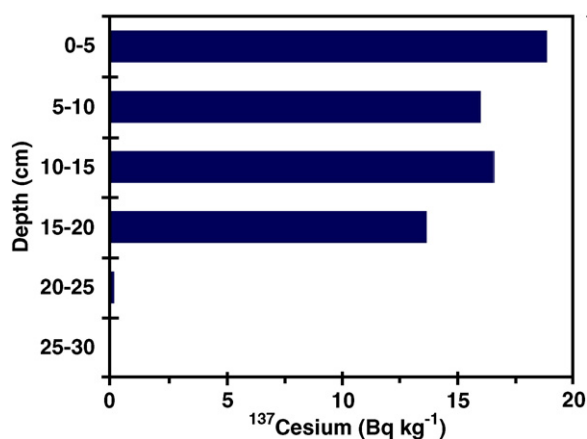


Fig. 1. Vertical distribution of ¹³⁷Cs in soil profiles in a tilled corn [*Zea mays* L.] in field 2 near Ames Iowa.

with both soil and SOC being redeposited within the field as well as being moved off the field (Harden et al., 1999; Smith et al., 2001; McCarty and Ritchie, 2002; Ritchie and McCarty, 2003). Understanding the patterns and processes involved in SOC redistribution across agricultural landscapes is key to understanding the potential for SOC sequestration in agricultural systems as well as the development models that can predict SOC distribution patterns on the landscape. Most studies have concentrated on the field scale using grid sampling and various mapping techniques to study the relationship between soil redistribution and SOC (i.e., VandenBygaart, 2001; Hao et al., 2001; Pennock and Frick, 2001; Ritchie and McCarty, 2003). The purpose of this study was to use grid-sampling techniques to evaluate fallout ¹³⁷Cesium (¹³⁷Cs) distribution on the landscape as a

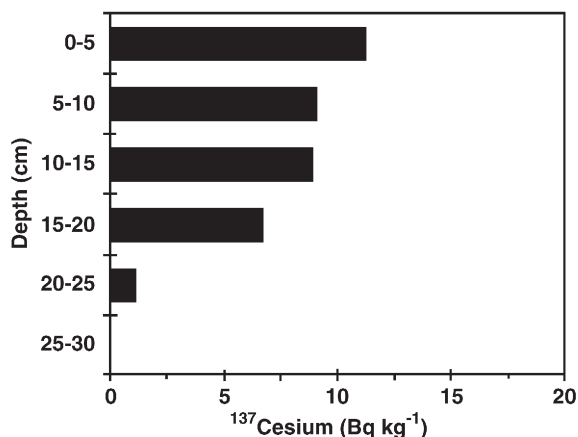


Fig. 2. Vertical distribution of ¹³⁷Cs in a tilled corn [*Zea mays* L.] field at the OPE³ field site in Maryland.

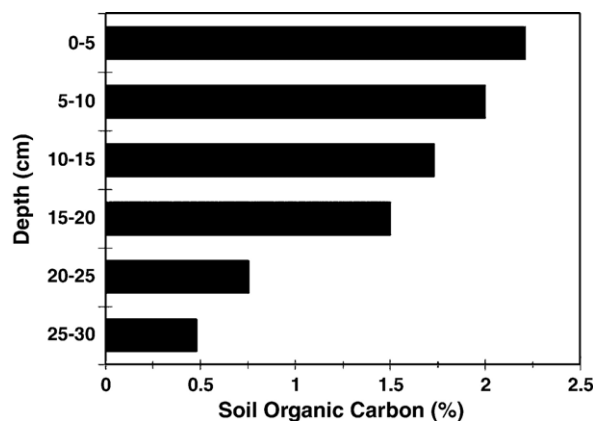


Fig. 3. Vertical distribution of SOC in a tilled corn [*Zea mays* L.] at the OPE³ field in Maryland.

tool to understand the spatial and temporal redistribution patterns of soil and SOC in tilled agricultural ecosystems with the emphasis on the role that terrain properties play in these distribution patterns.

2. Materials and methods

2.1. Sample sites

Single use tilled agricultural fields were sampled in Maryland and Iowa. The Maryland field is located on the Optimizing Production Inputs for Economic and Environmental Enhancement (OPE³) research watershed (Gish et al., 2003) in the Northern Coastal Plains physiographic province at the USDA Agriculture Research Service (ARS), Beltsville Agriculture Research Center near Beltsville, Maryland, USA. The sampled area is a tilled field that is approximately 25 h at an approximate

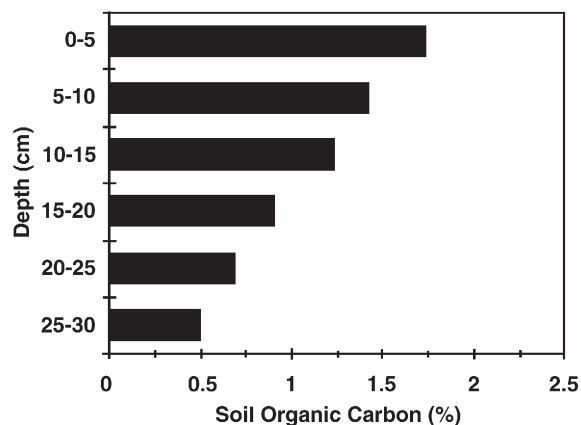


Fig. 4. Vertical distribution of SOC in a tilled corn [*Zea mays* L.] field 2 in Iowa.

Table 1

Mean and standard deviation for the field measurements for soil organic carbon, soil redistribution (negative values are erosion sites while positive values are deposition sites), and ^{137}Cs

Site	Number of samples	Soil organic carbon (%)	Soil redistribution ($\text{t ha}^{-1} \text{ year}^{-1}$)	^{137}Cs (Bq m^{-2})
Iowa (field 1)	230	$2.42 \pm 1.04\text{a}$	$0.1 \pm 32.4\text{a}$	$2624 \pm 1462\text{a}$
Iowa (field 2)	229	$2.34 \pm 0.88\text{a}$	$-3.5 \pm 21.6\text{a}$	$2354 \pm 1054\text{b}$
Maryland	273	$1.50 \pm 0.35\text{b}$	$-1.8 \pm 8.0\text{a}$	$2583 \pm 478\text{a}$

Means with different letters are significantly different at the 0.05 level of probability.

elevation of 40 m a.s.l. Mean annual precipitation is 1035 mm with a range from 547 to 1584 mm for the 1871–2000 period. Mean annual temperature is approximately 13°C with monthly averages ranging from 4°C in February to 27°C in July for the same period. The soils of the tilled areas are Hapludults, Paleudults and Fragiudults. The native vegetation of the area is pine [*Pinus* spp.] and hardwood [*Quercus* spp., *Acer* spp.] forest. The field has been tilled and planted in corn [*Zea mays* L.] since 1998. Prior to 1998, the field was used as a pasture for swine research.

Two Iowa farm fields were sampled in the Des Moines Lobe Till Plain in Central Iowa near Ames, Iowa, USA with an area of approximately 15 ha each. The elevation of the sites is approximately 300 m a.s.l. Mean annual precipitation is 835 mm. Mean annual temperature is approximately 8°C ranging from -6°C in January to 22°C in July. The soils are Hapludolls, Endoaquolls and Calciaquolls. The native vegetation is short grass prairie. Two farm management units on different operational farms were sampled. Both fields have tile drains with no surface inlets. The fields are in a corn [*Z. mays* L.] and soybean [*Glycine max* (L.) Merr.]

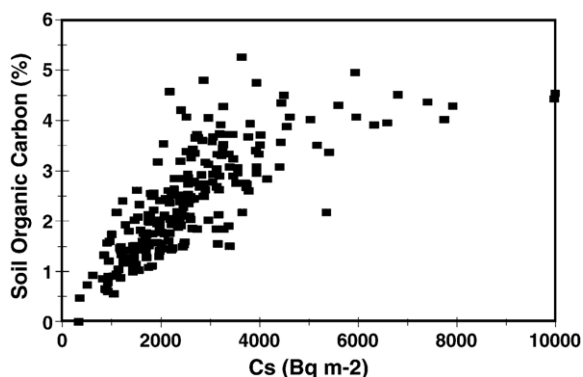


Fig. 5. Plot of the relationship between ^{137}Cs (Bq m^{-2}) and soil organic carbon (%) for field 1 in Iowa.

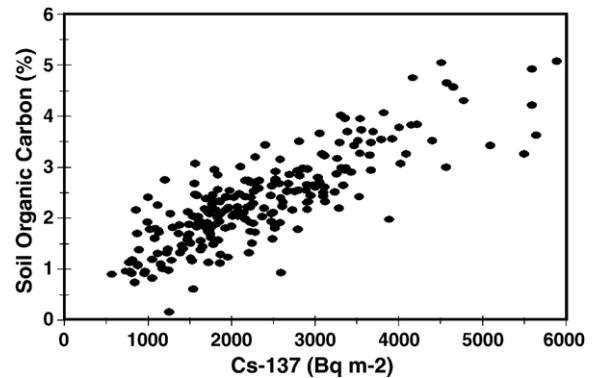


Fig. 6. Plot of the relationship between ^{137}Cs (Bq m^{-2}) and soil organic carbon (%) for field 2 in Iowa.

rotation alternating each year (Jaynes et al., 2003; Parkin and Kaspar, 2003; Kaspar et al., 2004).

2.2. Soil sampling

In the Maryland field, three soil samples were collected of the 0–30 cm layer using a 3.2 cm (1.25 inch) diameter push probe at each sample site on a 30 m grid pattern across the research area. The three samples were combined for analyses. Other soil profiles samples were collected by 5 cm depth increments to 40 cm using a 10 cm plastic pipe along four transects in the field (McCarty and Ritchie, 2002; Ritchie and McCarty, 2003).

In Iowa, three soil samples were collected for the 0–30 cm layer on a 25 m grid in each field using a 3.2 cm (1.25 in.) diameter push probe. The three samples were combined for analyses. Deeper soil samples were collected of the 30–50 cm layer at sites of deposition. Soil profile samples were also collected in 5 cm increments to a depth of 1 m at selected sites to measure the depth distribution of ^{137}Cs and SOC.

Reference soil samples were collected in areas where no apparent soil redistribution had occurred since the mid 1950s and used to determine baseline ^{137}Cs input to the area. At least six reference sites were collected within 2 km of the study fields in Maryland and Iowa.

All soil sample sites were surveyed with a code based Geographic Positioning System (GPS) (Trimble Geoexplorer XT¹) and are accurate to approximately 1 m. In the three fields, a RTK (real-time kinematic) GPS unit installed on an ATV (all terrain vehicle) vehicle was

¹ Trade names are included for the benefit of the reader and do not imply an endorsement of or a preference for the product listed by the U.S. Department of Agriculture.

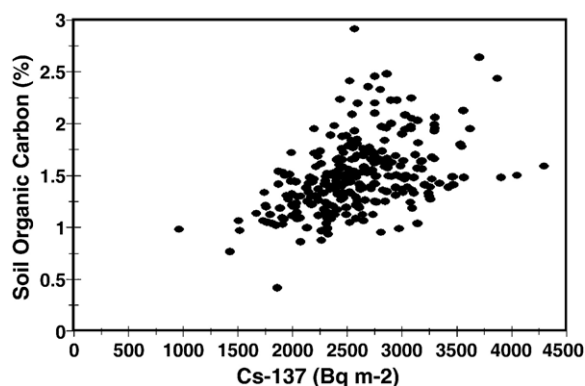


Fig. 7. Plot of the relationship between ^{137}Cs (Bq m^{-2}) and soil organic carbon (%) for the field in Maryland.

used to measure transects at approximately 5 m spacing (Kaspar et al., 2004; Venter et al., 2004) across the sampled area. Measurement accuracy was approximately 5 cm for location and elevation. A continuous 2 m elevation grid DEM (digital elevation map) was created by kriging the RTK data using Geostatistical Analyst in ArcGIS (ESRI, 2004) for the three fields. Elevation for each soil sample site was determined from these DEMs.

2.3. Sample analysis

The composited soil samples were dried, ground and screened through a 2 mm sieve. Total carbon (%) and nitrogen (%) were measured by dry combustion using a Leco CNS 2000 elemental analyser (Nelson and Sommers, 1996) on a sub-sample of the dried composited soil sample that had been ground to a very fine powder with a roller grinder. Calcium carbonate (CaCO_3) was measured by ashing the soil samples in a furnace (420°C for 16 h) and reanalysing the ashed sample for the remaining C in CaCO_3 . SOC was calculated from the difference between total carbon and CaCO_3 carbon.

The dried soil samples sieved to pass through a 2 mm screen were placed in Marinelli beakers and sealed for ^{137}Cs analyses. Analyses for ^{137}Cs were made by gamma-ray analysis using a Canberra Genie-2000 Spectroscopy System that receives input from three Canberra high purity coaxial germanium crystals ($\text{HpC} > 30\%$ efficiency) into 8192-channel analysers. The system is calibrated and efficiency determined using an analytic mixed radionuclide standard (10

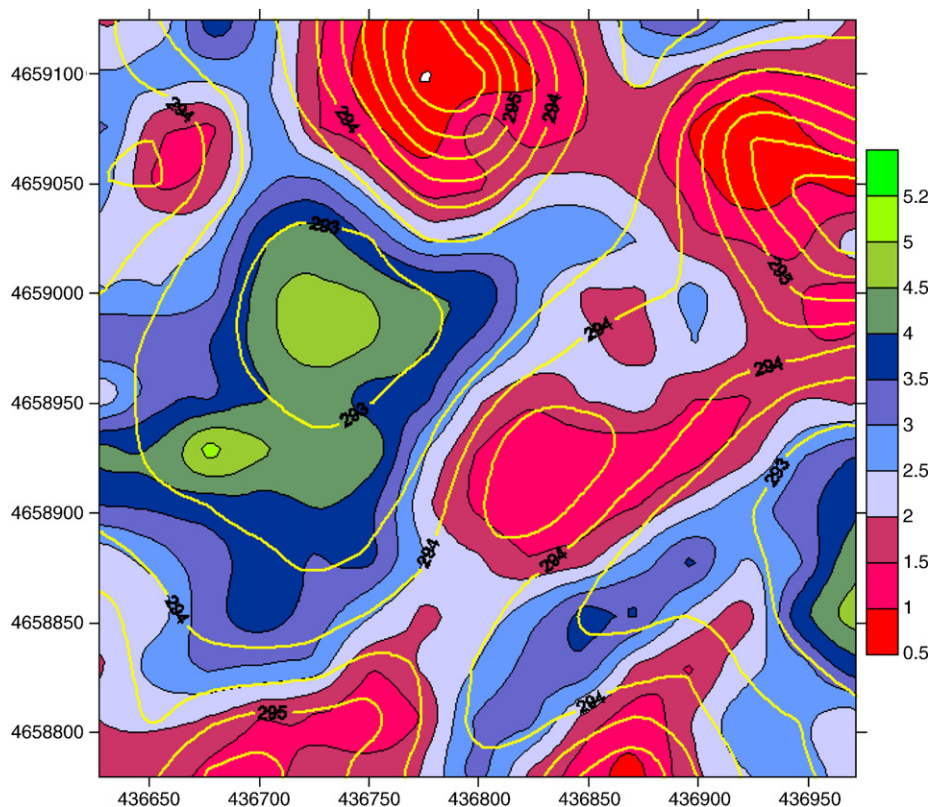


Fig. 8. Spatial distribution of SOC and surface elevation for Iowa field 1. Color scale is SOC (%) and yellow lines are elevations (m). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

nuclides) whose calibration can be traced to U.S. National Institute of Standards and Technology. Measurement precision for ^{137}Cs is $\pm 4\%$ to 6% and expressed in Becquerels per gram (Bq kg^{-1}) or Becquerels per square meter (Bq m^{-2}).

2.4. Soil redistribution

Soil redistribution (erosion or deposition) rates and patterns were calculated for each soil sample site based on the ^{137}Cs concentrations in the soil and models that convert ^{137}Cs measurements to estimates of soil redistribution rates (Ritchie and McHenry, 1990; Walling and He, 1999, 2001). The Mass Balance Model 2 (Walling and He, 2001) that uses time-variant ^{137}Cs fallout input and consideration of the fate of freshly deposited fallout was used to calculate soil redistribution rates. Sample sites with less ^{137}Cs than the ^{137}Cs at the reference sites are assumed to be eroding while sites with more ^{137}Cs than the ^{137}Cs the reference sites are assumed to be deposition sites. A plough depth of 25 cm was used to convert ^{137}Cs activity to erosion/deposition rates.

2.5. Terrain properties

The elevation and location data for each sample site were used with Surfer (Golden Software, 2002) to produce a DEM of the elevation in each field by kriging. Terrain attributes of each grid cell in this DEM (i.e., slope (the maximum rate of gradient change in elevation), plan curvature (curvature surface perpendicular to the gradient slope, values are negative for curvatures that are convex and positive for curvatures that are concave) profile curvatures (curvature of the surface in direction of the gradient slope, values are negative for curvatures that are convex and positive for curvatures that are concave) were calculated using Surfer software algorithms. Surfer was also used with field measurements and location data to create spatial maps for erosion/deposition ($\text{t ha}^{-1} \text{ year}^{-1}$), SOC (%) and ^{137}Cs (Bq m^{-2}), and then to calculate values of each for each grid cell for comparison with the terrain attributes. Statistical analyses of the field measurements and calculated grid cell values were made using Statistix software (Analytical Software, 2003). One-way ANOVA and Tukey's pairwise comparison were used to examine differences between means.

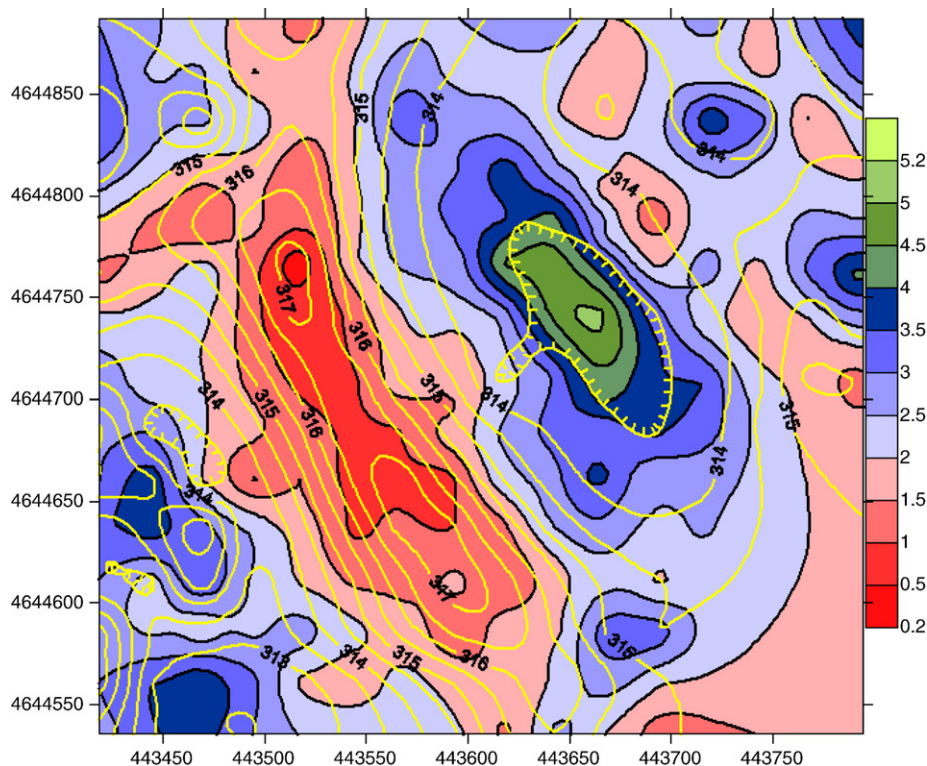


Fig. 9. Spatial distribution of SOC and surface elevation for Iowa field 2. Color scale is SOC (%) and yellow lines are elevations (m). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Results and discussion

^{137}Cs was uniformly distributed in the tilled layer in these agricultural fields (Figs. 1 and 2). Tilling depths ranged between 15 and 25 cm in the fields. ^{137}Cs depth distribution is typical of agricultural soils where tillage operations mix ^{137}Cs in the tilled layer of the profile (Walling and He, 1999; Ritchie and McCarty, 2003). In depositional areas on the fields, ^{137}Cs distribution was deeper than the tilled depth indicating the redistribution and subsequent redeposition of eroded material within the field. However, ^{137}Cs was not found below 30 cm in the soil profiles at the sampled sites. At the reference sites, ^{137}Cs showed an exponential decrease with depth typical of undisturbed sites (Walling and He, 1999; Ritchie and McCarty, 2003). SOC was highest in the surface layers and decreased slowly through the tilled layer with greater decreases with depth below this tilled layer at the Maryland (Fig. 3) and Iowa fields (Fig. 4).

The mean and standard deviation for the field measurements of SOC (%), ^{137}Cs (Bq m^{-2}) and soil redistribution ($\text{t ha}^{-1} \text{ year}^{-1}$) are given in Table 1. SOC was almost 1% higher in the soils of the grassland area in Iowa and statistically different from SOC in the Coastal Plains area of Maryland (Lal et al., 1998). SOC concentrations were related to soil redistribution rates in the Iowa fields. Field 2 in Iowa had higher erosion rates and lower SOC than field 1 in Iowa. While the SOC rates were significantly different, the soil redistribution rates were not significantly different for the three fields based on the field measurements. The ^{137}Cs (Bq m^{-2}) and soil redistribution ($\text{t ha}^{-1} \text{ year}^{-1}$) data had high coefficient of variation so that significant differences were less evident.

A statistically significant relationship between ^{137}Cs (Bq m^{-2}) and SOC (%) was found at all three fields (Figs. 5, 6 and 7), although the R^2 values are low (0.55, 0.68 and 0.21 for Iowa field 1, Iowa field 2 and the Maryland field, respectively). SOC increases as ^{137}Cs

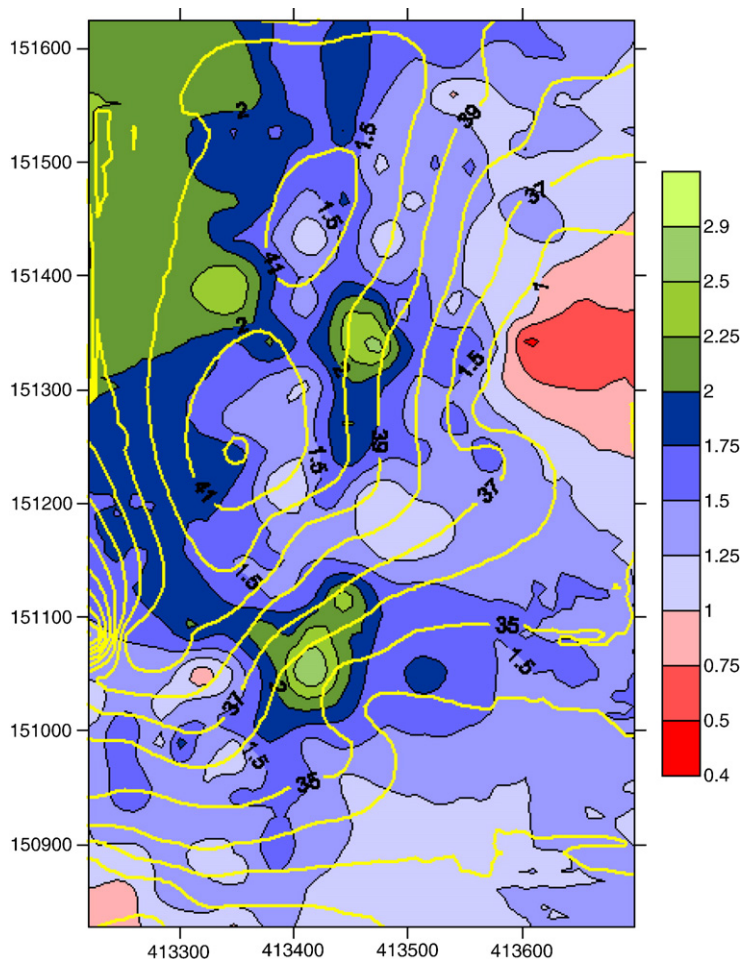


Fig. 10. Spatial distribution of SOC and surface elevation for the Maryland field. Color scale is SOC (%) and yellow lines are elevations (m). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2

Mean and standard deviation for the calculated grid-cell values for soil organic carbon, soil redistribution (negative values are erosion sites while positive values are deposition sites) and ^{137}Cs based on the kriged data from field measurements

Site	Number of samples	Soil organic carbon (%)	Soil redistribution ($\text{t ha}^{-1} \text{ year}^{-1}$)	^{137}Cs (Bq m^{-2})	Slope (%)
Iowa (field 1)	9604	2.42±0.98a	0.7±26.1a	2662±1382a	1.26±0.79c
Iowa (field 2)	9016	2.26±0.77b	−6.0±18.6c	2129±842c	1.59±1.13a
Maryland	5782	1.51±0.35c	−1.4±6.4b	2612±387b	1.36±1.09b
All	24402	2.15±0.87	−2.3±20.4	2453±1054	1.41±1.01

Means with different letters are significantly different at the 0.05 level of probability.

increases indicating that they are probably moving along similar physical pathways. It is known that ^{137}Cs is strongly adsorbed to the fine soil fraction and any movement is associated with the physical movement of these fines (Ritchie and McHenry, 1990). SOC moves with these fines also (Gregorich et al., 1998; Harden et al., 1999; Lal, 2004; Janzen, 2004).

The spatial distribution patterns of SOC and elevation in the three fields are shown in Figs. 8, 9 and 10. Iowa field 1 (Fig. 8) and field 2 (Fig. 9) have hummocky surfaces with small depressions and ridges that are associated with glacial stagnation and melting during the last deglaciation. The depressions are generally considered closed in the hydrologic sense with tile drainage at these sites as is common throughout the area. The fields are nearly closed basins with most of runoff being collected in the low areas (pot holes) in the fields. In Figs. 8 and 9, the areas of high SOC are in the

Table 3

Mean and standard deviation for the calculated grid-cell values compared by soil redistribution

Soil redistribution	Number of samples	Soil organic carbon (%)	Soil redistribution ($\text{t ha}^{-1} \text{ year}^{-1}$)	^{137}Cs (Bq m^{-2})	Slope (%)
Erosion	14762	1.90±0.94a	−13.2±11.3a	2070±675a	1.52±0.94a
Deposition	9620	2.53±0.92b	14.4±19.9b	3041±1243b	1.22±1.08b
All		2.15±0.87	−2.3±20.4	2453±1054	1.41±1.01

Sites losing soil are listed as erosion grid cells while sites gaining soil are listed as deposition grid cells. The three fields have been combined. Means with different letters are significantly different at the 0.05 level of probability.

Table 4

Mean and standard deviation for the calculated grid-cell values compared by slope class

Slope (%)	Number of samples	Soil organic carbon (%)	Soil redistribution ($\text{t ha}^{-1} \text{ year}^{-1}$)	^{137}Cs (Bq m^{-2})
<1	10008	2.56±1.00a	3.7±24.2a	2892±1280a
1–2	8992	1.97±0.60b	−4.5±13.9b	2313±631c
2–3	3540	1.69±0.54c	−10.2±10.2c	1926±674d
3–4	1499	1.53±0.64d	−10.7±10.7d	1638±827e
>4	274	1.95±0.80b	−5.9±18.4b	2064±1045b
All		2.15±0.87	−2.3±20.4	2453±1054

The three fields have been combined. Means with different letters are significantly different at the 0.05 level of probability.

depressions where water collects and soil deposition is occurring. The ridges have lower SOC and represent area where soil loss is occurring. The relationship between SOC and elevation is especially strong in the Iowa fields (Figs. 8 and 9). SOC was lower in field 2 where soil erosion was higher. At the Maryland field (Fig. 10), the field slopes toward a riparian area and patterns of SOC are related to the drainage patterns and depression in the field where water movement slows and soil collects.

Using Surfer's algorithms, SOC (%), ^{137}Cs (Bq m^{-2}) soil redistribution (t ha^{-1}) and slope (%) in direction of steepest gradient descent) were calculated for each grid cell (Table 2). The three fields were significantly different from each other for these four calculated grid cell attributes. In general, the means and standard deviations for these grid cell estimates follow the same patterns and are similar in absolute value to the field measurements (Table 1). Erosion was greatest on the field (Iowa field 2)

Table 5

Mean and standard deviation for the calculated grid-cell values compared by plan curvature (i.e., curvature of the surface perpendicular to the gradient direction of the slope)

Slope shape	Number of samples	Soil organic carbon (%)	Soil redistribution ($\text{t ha}^{-1} \text{ year}^{-1}$)	^{137}Cs (Bq m^{-2})	Slope (%)
Concave	12220	2.44±0.93a	1.7±22.5a	2727±1173a	1.22±1.01a
Convex	12782	1.85±0.68b	−6.3±17.1b	2179±834b	1.59±0.97b
All		2.15±0.87	−2.3±20.4	2453±1054	1.41±1.01

The three fields have been combined. Means with different letters are significantly different at the 0.05 level of probability.

Table 6

Mean and standard deviation for the calculated grid-cell values compared by profile curvature (i.e., curvature of the surface in the gradient direction of the slope)

Slope shape	Number of samples	Soil organic carbon (%)	Soil redistribution ($\text{t ha}^{-1} \text{ year}^{-1}$)	^{137}Cs (Bq m^{-2})	Slope (%)
Concave	14782	2.34±0.90a	−0.2±21.5a	2626±1112a	1.33±0.95a
Convex	9620	1.71±0.61b	−7.2±16.5b	2055±771b	1.59±1.11b
All		2.15±0.88	−2.3±20.4	2453±1054	1.41±1.01

The three fields have been combined. Means with different letters are significantly different at the 0.05 level of probability.

with the steepest average slope. Also SOC was lower in the field with the greater erosion and steeper slopes.

Combining the data from the three fields and comparing eroding and deposition grid cells (Table 3) shows that the average SOC concentration at the depositing sites was significantly greater than the SOC at the eroding sites. The average slope was greater for the eroding grid cells than for the grid cell with soil deposition. The grid cells with higher slopes tended to be on the ridges. Comparing slopes for the grid cell (Table 4) shows that SOC decreases and soil loss increases as slope increases. In the depression (slopes < 1%) soil deposition and higher SOC values were found. The change in pattern for both SOC and soil redistribution for slopes greater than 4% may be a statistical anomaly due the limited number of grid cells in this slope category and the way in which Surfer calculates grid cell values for edge grid cells.

Tables 5 and 6 compare the relationship between slope shape and the SOC and soil redistribution. Whether comparing slope shape in the gradient direction of the slope or perpendicular to the gradient direction of the slope, concave slopes have higher SOC and less soil loss than the convex slopes. These patterns are the same as has been shown in other studies (Gregorich et al., 1998; Pennock and Frick, 2001; Mueller and Pierce, 2003; Kaspar et al., 2004). The gradient slopes were less in the concave slope indicating a convergence and potential slowing of run off which would allow water to slow and eroded soil particles to be deposited.

4. Conclusions

^{137}Cs and SOC concentrations of upland soils are significantly correlated in our study fields. In the upland areas, eroding soils, determined using ^{137}Cs measure-

ments, have significantly less SOC than soils in deposition areas. These data suggest that ^{137}Cs patterns may be used to help understand SOC dynamics on the landscape. Different productivity and oxidation rates of SOC of eroded versus deposited soil would also contribute different patterns of SOC on the landscape. However, the strong significant relationships between ^{137}Cs and SOC concentrations in the upland soil suggest that they are moving along similar physical pathways in these systems. The strong relationship between terrain attributes and SOC also suggest that models can be developed to predict patterns of soil and SOC redistribution on the landscape providing potential insights into management system that will enhance sequestration of carbon in agricultural ecosystems.

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